A Novel MAI Reduction Method Using Longer M-sequences for Multiuser Detection in DS/CDMA Communication Systems

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Abstract

In this paper, we consider the problem of Multiuser Detection (MUD) in Direct Sequence/Code Division Multiple Access (DS/CDMA) communication systems. The optimum detector for MUD is the Maximum Likelihood (ML) detector, but its complexity is very high and involves an exhaustive search to reach the best fitness of the transmitted and received data. Thus, there has been considerable interest in suboptimal multiuser detectors with less complexity and reasonable performance. If we look to the problem from an optimization viewpoint, what makes our work difficult is high interaction and Epistasis among variables which should be optimized. We propose to work on the problem and try to reduce its complexity instead of using more complex and powerful optimization algorithms. To do so, we analyze problem carefully and propose a new method to overcome Epistasis. In this paper, by using sign detector and longer code lengths in DS/CDMA system, a simple detector will be proposed. This method is compared with ML and two model-free optimization methods: Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO) algorithms which have been used for MUD in DS/CDMA. Simulation results show our method dramatic efficiency.

Keywords

Direct Sequence/Code Division Multiple Access (DS/CDMA); Multiuser Detection; Epistasis; M-sequence code length; Sign Detector

Introduction

In a DS/CDMA system, the receiver is a Matched Filter Bank (MFB), which comprises the conventional detector (sign detector). This type of receiver is unable to optimally recover the signal, when the channel is contaminated by additive white Gaussian noise (AWGN), and suffers from flat or frequency selective fading; because the DS/CDMA signal is affected by Multiple Access Interference (MAI) and also by the Near-Far Ratio (NFR) [1]. In fact, the signature signals of different users are not completely orthogonal to each other, and cross correlation among these signals results in multiple access interference. Therefore, the conventional matched filter detector, as in single user communication, is no longer effective and causes many problems [2]. In 1986, Verdu in [3] proposed the optimum multiuser detector (OMUD) which consists of a bank of matched filters followed by a maximum likelihood sequence estimator (MLSE). The MLSE detector generates a maximum likelihood sequence, $\hat{b}$, which is associated with the transmitted sequence, as presented in Fig. 1 [1]. The vector b is estimated in order to maximize the sequence transmission probability given that $r(t)$ is received; where $r(t)$ is extended for all messages, considering all the transmitted messages with the same transmission probability [1]. The OMUD has a computational complexity which grows exponentially with the number of users. Thus, since CDMA systems could potentially have a large number of users, the OMUD is impractical to implement for them. Therefore, many researches have focused on sub-optimum detectors with less complexity and a performance which is almost as high as the OMUD. Alternative detectors for OMUD include the Decorrelator proposed by Verdu in [3] and the MMSE detector recommended by Poor and Verdu in [4]. These algorithms have reasonable computational complexity, and their performance is comparable to that of the optimum receiver, but they yield a degraded communication system in the sense of BER [5].

According to the problem of ML detector, many methods for suboptimal detection have been proposed. Some heuristic methods have been developed, such as genetic algorithm (GA). The first GA-based multiuser

detector (GA-MUD) was proposed by Juntti et al. [6] which assumed a synchronous CDMA system model communicating over an AWGN channel. After that in [7, 8] the new approach of GA is proposed. Tabu search algorithm [9] and simulated annealing algorithm (SAA) [10, 11] are the other new approaches of Multiuser detectors.

In fact, all the approaches for MUD are classified into two global approaches: the first is the proposition of a new suboptimal Multiuser detector with tradeoff between performance and complexity such as MUD based on Particle Swarm Optimization (PSO) and wavelet transform [12–17] and Ant Colony-based MUD in [18-21]. The second approach is the reducing of MAI and applying simple conventional detector. In other words, instead of using more complex methods for multiuser detection, we try to reduce Multiple Access Interference in DS/CDMA system and then apply simple detector such as conventional detector. For this purpose, we must introduce Epistasis.

Epistasis is a phenomenon where the effects of one gene are influenced by one or several other genes. The word “Epistasis” was used by William Batson [22] in genetic science to describe a gene that affects the operation of other genes.

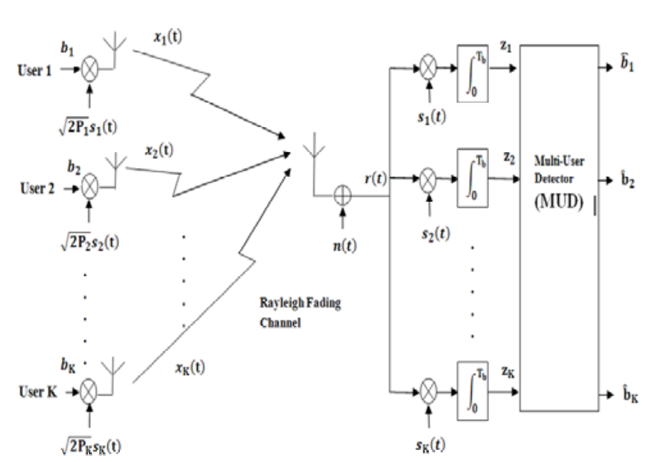

FIG. 1 BASEBAND DS/CDMA BLOCK DIAGRAM, RECEIVER WITH MUD [1].

In optimization literature, Epistasis is used with similar definition: the interaction between optimization variables [23]. Highly Epistatic problems are very more difficult to be optimized. In fact in every nontrivial optimization problem, there should be at least a little degree of Epistasis; otherwise, the problem will be trivial [24]. Since in such cases, the N-variable non-Epistatic function can be divided into N separate functions each with one variable. In our optimization problem, MAI is the cause of Epistasis. So to design a suitable detector for DS/CDMA, we try to reduce Epistasis (here, MAI) and use conventional detector rather than using more complex Multiuser detectors.

MAI is the result of correlation between signature signals of users. Correlation could be shown in square matrix form in which elements on main diagonal are autocorrelations and elements outside main diagonal are cross correlations between the signature signals of users. For M-sequence codes if code with higher length is used, it will be claimed that autocorrelation elements will remain constant but cross correlation elements decrease proportional to inverse of code length [25], i.e. longer M-sequence codes, less MAI. It is important to note that long codes have some advantages such as interference randomization and improving the system capacity. Based on the above, our analysis focuses on DS/CDMA systems with long spreading codes. Our proposed method is compared to the ML detector, Matched Filter detector, Ant Colony and PSO-based detectors, and we show that the performance of the proposed method is better with less complexity.

The remainder of this paper is organized as follows: Section 2 describes our asynchronous CDMA system and section 3 highlights the simple method used to implement our proposed detector. The simulation results are presented in Section 4, while Section 5 provides comparison of the complexities associated with our algorithm and several effective methods. Finally, some conclusions are dawn in Section 6.

System Model

In a DS/CDMA system with binary phase-shift keying modulation (BPSK) shared by k asynchronous users, as illustrated in Fig. 1, the k-th user transmitted signal is given by [1]:

$$x_k(t) = \sqrt{2p_k}\sum_i b_k^{(i)} s_k\left(t - iT_b\right)\cos\left(\omega_c t\right). \tag{1}$$

Where p_k represents the k-th user transmitted power; $b_k^{(i)}$ is the i-th BPSK symbol with period T_b; ω_c is the carrier frequency and $s_k(t)$ corresponds to the spreading sequence defined in the interval $[0,T_b)$:

$$s_k(t) = \sum_{n=0}^{N-1} p\left(t - nT_c\right)c_{k,n}; \quad 0 \le t \le T_b \tag{2}$$

Where $c_{k,n} \in \{-1,+1\}$ is the n-th chip of the sequence with length N used by the k-th user; T_c is the chip period and the spread spectrum processing gain, $\frac{T_b}{T_c}$ is equal to N ; the pulse shaping $p(t)$ is assumed rectangular with unitary amplitude in the interval $[0,T_c)$ and zero outside.

Assuming a frame with I bits for each user propagating over L independent slow Rayleigh fading paths, the baseband received signal in the base station is [1]:

$$r(t)=\sum_{i=0}^{I-1}\sum_{k=1}^{K}\sum_{l=1}^{L}A_k b_k^{(i)} s_k(t-\tau_k)*h_k^{(i)}(t)+w(t). \tag{3}$$

Where K is the number of active users, $t \in [0,T_b)$. The amplitude A_k is assumed constant for all I transmitted bits, $b_k \in \{-1,+1\}$ is the transmitted information bit, s_k denotes a copy of the signature sequence assigned to the k-th user and τ_k represents the random delay associated to the k-th user; the complex low-pass impulse response of the channel for the k-th user over the i-th bit interval can be written as [1]:

$$h_k^{(i)}(t)=\sum_{l=1}^{L}a_{k,l}^{(i)}\delta(t-\lambda_{k,l}). \tag{4}$$

Where $\lambda_{k,l}$ is the propagation delay and $a_{k,l}^{(i)}$ is the complex channel coefficient whose amplitude has Rayleigh distribution, and its phase is uniformly distributed over $[0,2\pi]$. Finally, w(t) represents the AWGN with bilateral power density equal to $\frac{N_0}{2}$.

Using vectorial notation, Equation. (3) can be stated as [1]:

$$r(t)=\sum_{i=0}^{I-1}s^T(t-iT_b)Aa^{(i)}b^{(i)}+w(t). \tag{5}$$

Where $A=diag[A_1 I, A_2 I, ..., A_k I]$ is the diagonal matrix for the users' amplitude including the path losses and shadowing effects, and $I_{L\times L}$ is the identity matrix with a dimension equal to L ; s is the vector of users signature sequence, and a is the diagonal channel gain matrix as:

$$a^{(i)}=diag\left[a_{1,1}^{(i)},...,a_{1,L}^{(i)},a_{2,1}^{(i)},...,a_{2,L}^{(i)},...,a_{K,L}^{(i)}\right] \tag{6}$$

And the data vector is given by:

$$b^{(i)}=\left[b_1^{(i)},b_2^{(i)},...,b_K^{(i)}\right]^T \tag{7}$$

representing the 1×L k-th user bit vector.

If we use the conventional Rake receiver which consists of a bank of KL filters matched to the users' signature sequence [2], then the output for the i-th bit interval can be expressed as [1]:

$$y_{k,l}^{(i)}=\int_{-\infty}^{+\infty}r(t)s_k(t-iT_b-\tau_{k,l})dt=A_k T_b \rho_{k,l}^{(i)}b_k^{(i)}+I_{k,l}^{(i)}+n_{k,l}^{(i)}. \tag{8}$$

Where the first term corresponds to the desired signal, the second refers to the MAI over the l-th multipath component of the k-th user, and the last represents the filtered AWGN. It should be noted that the auto-interference term is neglected for simplicity. MAI is the result of cross correlation between signature signals of users as expressed [1]:

$$R_{j,k}(\tau,i)=\int_0^{T_b}s_j(t)s_k(t+iT_b+\tau)dt \tag{9}$$

If we use the Rake receiver, we need to estimate some parameters such as channel coefficients and delay (τ). When the number of users increases, the significance of interference rises and owing to this fact, the conventional detector performance in MUD is degraded. As mentioned in the previous section, we use the optimum detector to solve this problem. The optimum detector is the maximum likelihood sequence detector that selects the most likely sequence of transmitted bits given by the observations at the receiver. In this context, the K-user, L-paths, I-frame and asynchronous channel scheme can be viewed as a KLI-user synchronous channel scheme, and then the KLI-user vector B can be written as [1]:

$$B=\left[b^{(0)^T},b^{(1)^T},\ldots,b^{(I-1)^T}\right]^T \tag{10}$$

Based on [27], Verdu proved that in order to select the maximum likelihood sequence B, we must maximize the log likelihood function (LLF):

$$f\left(B\right)=2\operatorname{Re}\left\{B^T a^H A y\right\}-B^T aARAa^H B. \tag{11}$$

Where R is the cross correlation matrix and y is the output vector as [1]:

$$y=\left[y^{(0)^T},y^{(1)^T},\ldots,y^{(I-1)^T}\right]^T \tag{12}$$

Neglecting the channel effect, we can state (11) in a simple form as [1]:

$$f\left(B\right)=B^T r-B^T RB. \tag{13}$$

Where r is the received signal and B is the transmitted sequence to be guessed and we neglect other parameters in (11) due to the channel effect. The complete frame with the estimated transmitted bits for all K users can be obtained through optimization of (13), resulting [1]:

$$\hat{B}=\arg\left\{\max_{B\in\{-1,+1\}^{IK}}\left[f\left(B\right)\right]\right\} \tag{14}$$

The OMUD attempts to find the best vector of data bits but because of high complexity and unfeasible implementation, it is an inefficient method for multiuser detection. Because of the high dimensionality of OMUD, all suboptimal algorithms try to find a solution following an objective function which is able to improve the performance of multiuser detection. These attempts try to reduce the complexity of OMUD and maximize the DS/CDMA mean performance. Most efforts concentrate on approaching the performance of ML algorithm with less complexity and reliable applicability along with the least possible error. In the next section, we propose our algorithm to achieve this goal and compare our algorithm to other efficient algorithms available in the literature.

Proposed Algorithm

Sign Detector

In conventional single user detection, the receiver for each user consists of a demodulator that correlates the received signal with the signature sequence of the user and passes the correlator output to the sign detector, which makes a decision based on the single correlator output. Thus the sign detector neglects the presence of the other users of the channel or equivalently assumes that the aggregate noise plus interference is white or Gaussian. Clearly if the signature sequences are orthogonal, the interference from other users vanishes and the conventional signal detector is optimum. Because it is not possible to design signature sequences for any pair of users that are orthogonal for all time offsets, thus the conventional detector is vulnerable to interference from other users [2].

Now we should choose between two options. Using more complex and powerful detectors to overcome MAI and give a suboptimum detector near ML detector, or try to eliminate Barriers mentioned above in sign detector method.

Epistasis and MAI

In genetic science, Epistasis is a phenomenon where the effects of one gene are influenced by one or several other genes. This concept exists in optimization problems too where the values of one optimization variables cannot be labeled (as good, bad and so on) without considering the status of other variables. For example consider the optimization test functions in tables 1 and 2. These functions are some of the most famous test functions which are commonly used in the literature [27-31]. In table 1 you can see some non-epistatic problems. In these problems you can optimize the objective function for each variable separately, while in the problems such as the ones in table 2, the important matter is the arrangement of the variables and their values beside each other. In such problems there is no superposition and the whole is something more than sum of the individuals. That extra comes from the information existing in the structure.

TABLE 1 FUNCTIONS WITH ZERO DEGREE OF EPISTASIS

Function	Formula
F_1	$\sum_{n=1}^{N} x_n^2$
F_2	$x\sin\left(4x\right)+1.1y\sin\left(2y\right)$
F_3	$10N+\sum_{n=1}^{N}\left[x_n^2-10\cos\left(2\pi x_n\right)\right]$

TABLE 2 EPISTATIC FUNCTIONS

Function	Formula
F_4	$\sum_{n=1}^{N}\left\{100\left[x_{n+1}-x_n^2\right]^2+\left[1-x_n\right]^2\right\}$
F_5	$0.5+\frac{\sin^2\left(\sqrt{x^2+y^2}\right)-0.5}{1+0.1\left(x^2+y^2\right)}$

Next, let us take a closer look at the LLF. Considering Equation (13), the objective function is comprised of two terms: $B^T r$ and $B^T RB$. For maximizing the $B^T r$ part, considering the fact that each element of B can only take the values of either 1 or -1, it is enough for each element of B to be either 1 or -1 according to the sign of corresponding element in r. Since the $B^T RB$ term is a square matrix, if the non-diagonal elements were small, it would be practically equal to $B^T B$. In this case, it is insignificant if the values of the elements of B are either 1 or -1. The main problem is that some non-diagonal matrix elements are not considerably small and cannot be assumed as negligible almost always. Because the matrix R is symmetric, these elements add terms of the type $2R_{ij}B_i^T B_j$ to the objective function. In this case if R_{ij} is positive, the fact that B_i^T and B_j bearing different sign helps increasing the value of the objective function, and if R_{ij} is negative, their similar signs help this fact. In other words, the problem variables are no longer independent and their interaction is influential.

In the first glance it seems that we should try to find the optimization methods which have potential ability to overcome this problem to some extent as in [13, 15]. But what if we could decrease the Epistasis and make the problem trivial. If we do this we can solve the problem with sign detector easily.

Using Longer M-Sequence Codes

If there is not much limitation on band width in communication system, cross correlation between codes can be decreased using longer M-sequence codes. In other words the probability of user interference will be reduced and this means that elements that are not on the main diagonal of matrix R, using this work, are decreased noticeably but the main diagonal elements are fixed.

For M-sequence codes if codes with higher length are used, cross correlation will be reduced according to (15) proportional to 1/N, [25] i.e. longer M-sequence codes, less Epistasis.

$$R_{ij}=\begin{cases}1 & if \quad i=j\\ \dfrac{1}{N} & if \quad i\neq j\end{cases} \tag{15}$$

So by using longer codes, Epistasis would be decreased and sign detector could be applied for detecting the transmitted signal with minimum error. This property is also verified for Gold codes or other codes that used in some communication systems for spreading signals. Therefore by using longer codes, the capacity of system is increased and the interference among users is decreased and consequently the simple and low complexity detectors can be applied for MUD.

For better presentation of MAI decreasing, one simulation is done and the average of cross correlation of users in different code lengths is evaluated and depicted in Fig. 2. In this figure, it is showed that increasing the code lengths reduced the cross correlation mean value exponentially rather than linearly. In fact the relation is followed by $y=ba^{-x}$ that y and x are presentations of cross correlation mean value and code lengths respectively. From simulation and using interpolation, the values of a and b are approximated as, b = 10.94 and a = 4. This fact verifies our method effectivity. Since by small increase in code-length a considerable decrease in MAI is obtained.

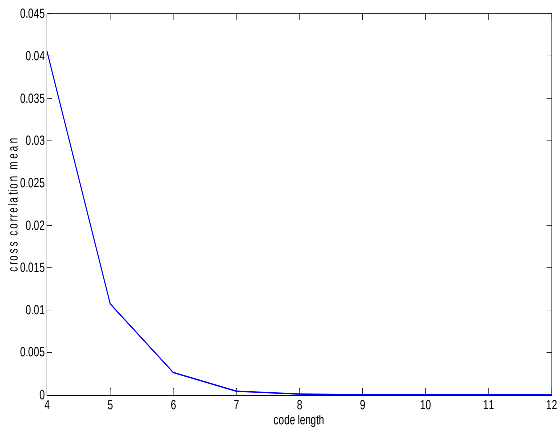

FIG. 2 CROSS CORRELATION MEAN VALUE VERSUS DIFFERENT CODE LENGTHS, THE EXPONENTIAL RELATION.

Numerical Results

In this section, the performance of the algorithm described in Section 3 is compared to Matched filter receiver (MF), Maximum Likelihood method (ML) and

two optimization-based algorithms, PSO and ACO considering the BER as the main figure of merit. The convergence of each algorithm versus optimization parameters is also provided. It is assumed that the communication system is asynchronous DS/CDMA MUD, over slow Rayleigh fading AWGN channel.

The numerical results were obtained based on the averaging of 1000 simulation runs;and these results were attained in identical systems and channel conditions in order to provide fair comparison to other algorithms. Simulation parameters are as follow:

TABLE 3 SIMULATION PARAMETERS

Modulation	BPSK
Spreading code	m-sequence
Communication system	Uplink asynchronous CDMA
User number (K)	20
Channel	AWGN with slow Rayleigh fading
Path number (L)	4
Path loss variance	-5 dB

The spreading sequences are selected as pseudo-noise (PN) m-sequence; in addition the number of active asynchronous users in the system is K=20; in all figures, it was assumed that the phases, amplitudes, channel gains and random delays of all users are perfectly known in the receiver, and users' power is:

$$E\left[\sum_{l=1}^{L}\left|a_{k,l}^{(i)}\right|^2\right]=1, \qquad for\ k=1,2,\ldots,K \tag{16}$$

In these simulations that will be seen, our proposed method is more effective and better in comparison to the two other algorithms, ACO and PSO.

In Fig. 3, a comparison between the proposed algorithm with comprehensive search in the space of parameters known as ML versus BER of communication system is proposed. From this figure, it can be seen that increasing the length of m-sequence code causes the BER decreasing. Especially in code length equal to 10, the difference between our algorithm and ML is negligible. So using m-sequence with length 10 is suitable and it is used for the following simulations. Of course notice that codes with higher lengths have more complexity and are not suitable for our purpose of simple and low complex method. This simulation is done in SNR 15 dB.

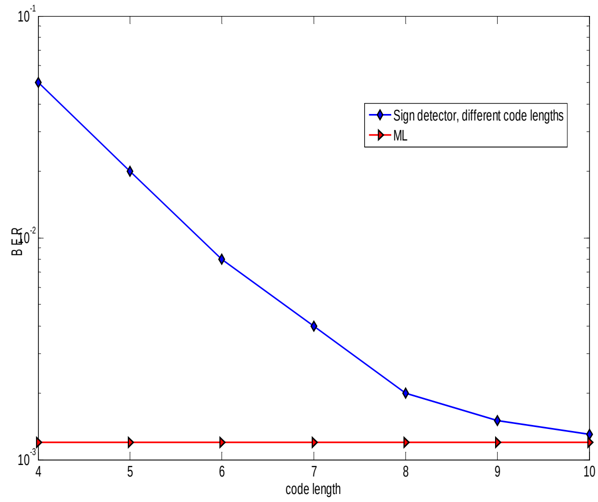

FIG. 3 THE BER COMPARISON BETWEEN ML AND PROPOSED ALGORITHM WITH DIFFERENT CODE LENGTHS (SNR=15 dB)

The main parameter of each communication system, BER, is discussed in Fig. 4. This property of the proposed algorithm is compared to ACO and PSO algorithms and also to ML and the worst case as Matched filter. It is revealed that although in low SNR, there is no main difference among the methods; the proposed algorithm in high SNR converges to optimum MUD and the BER of this method is less than that in ACO and PSO methods. This figure shows the unsuitability of the matched filter detector.

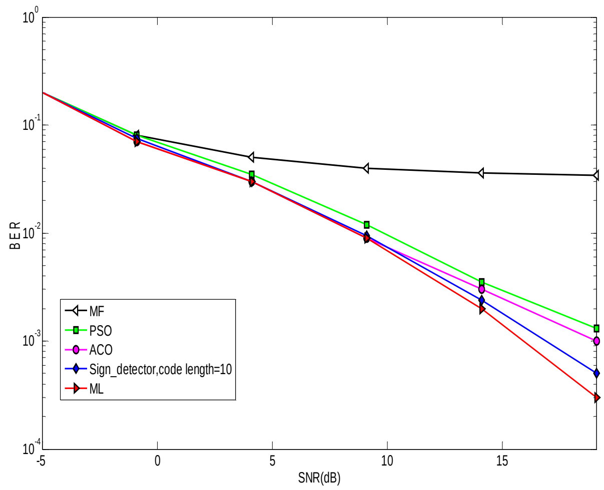

FIG. 4 BER OF THE PROPOSED ALGORITHM IN COMPARISON TO OTHER METHODS VERSUS SNR.

In Fig. 5, the effect of increasing the number of users on BER is analyzed for the classic algorithms and optimization-based techniques such as ACO and PSO. On the basis of this figure, it can be seen that the ACO and the proposed algorithm almost work similarly, and BER of these two algorithms does not considerably increase with increasing user numbers. It can also be observed that the performance of the

classic matched filter method is degraded substantially. This simulation is done for SNR 12 dB.

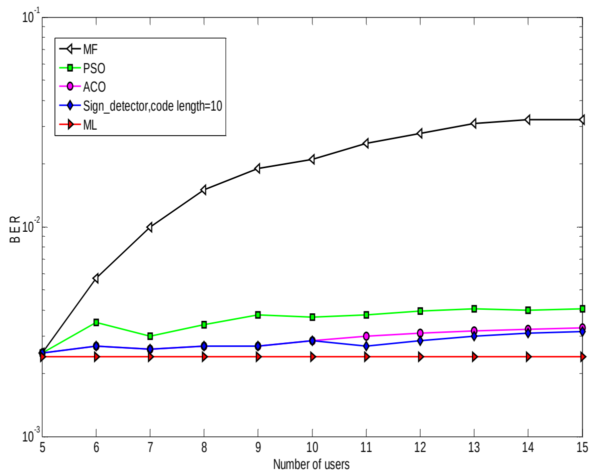

FIG. 5 BER OF THE PROPOSED ALGORITHM VERSUS NUMBER OF USERS IN COMPARISON TO OTHER METHODS. SNR IS FIXED AT 12 DB.

In Fig. 6, the proposed algorithm with different code lengths is implemented and the numerical results are depicted. It is observed that with the code length 10, the algorithm converges to optimum MUD in high SNRs. Of course, for the other code lengths less than 10 such as 8 and 6, the error is small and the convergence is acceptable to some extent. As seen from this figure, the proposed algorithm operates very well, and the convergence of this case is quite interesting.

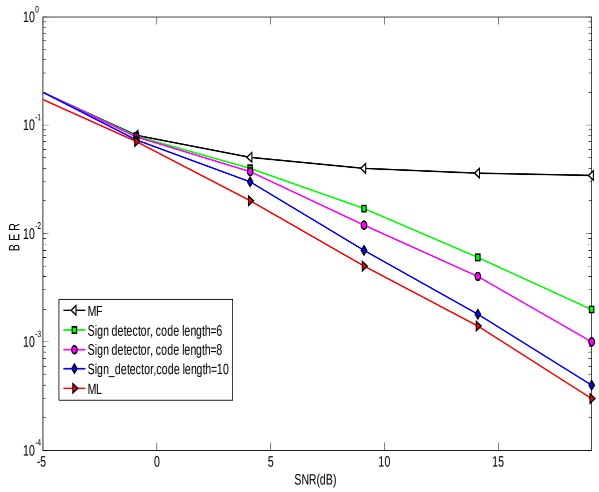

FIG. 6 BER OF THE PROPOSED ALGORITHM VERSUS SNR FOR DIFFERENT CODE LENGTHS, COMPARED TO ML AND MF.

Computational Complexity

A common form in order to compare algorithms' complexities can be done through the O notation, which means the order of magnitude associated with the algorithm complexity. But comparing algorithms only with O can be insufficient. In order to express the complexity of the analyzed algorithms, it is essential to determine which instructions are carried out and how many times they are processed [1]. Suppose the number of transmitted bits is I and the number of users is K . For OMUD, the number of operations increases exponentially with the number of users, i.e. 2^{KI} . For our proposed algorithm, the code length and the size of correlation matrix of m-sequence codes are the most important factors of calculation. After that, the sign detector is very simple and has no complexity. The complexity of correlation matrix by code length 10 is fixed and it is calculated and stored before receiver in database of the system to use when needed. Fig. 7 shows that the complexity associated with our proposed algorithm is much less than ML and comparable to matched filter and ACO detector.

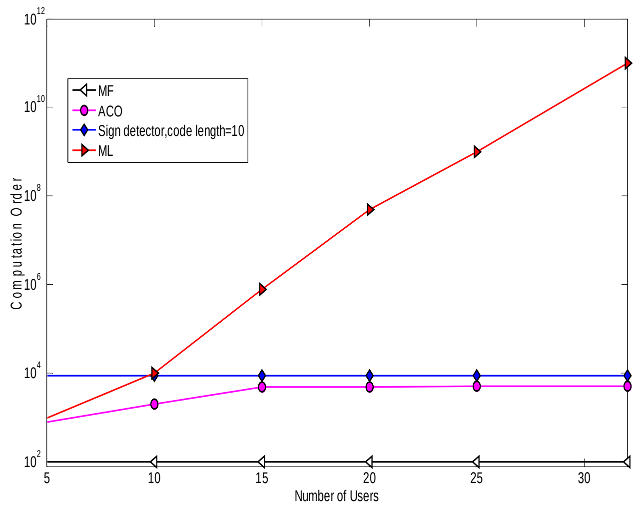

FIG. 7 COMPUTATION ORDER OF THE PROPOSED METHOD VERSUS THE NUMBER OF USERS, COMPARISON TO ACO, ML AND MATCHED FILTER METHOD.

Conclusions

In this paper, multiuser detection based on a new algorithm was implemented, and through presentation of m-sequence codes and sign detector, the desirable method was achieved. When compared to sub-optimal algorithms such as ACO and PSO, the new algorithm shows better performance, and in some cases, approaches the optimal ML algorithm with minimum error. This algorithm is quite efficient, and shows acceptable performance in code length equal to 10. Of course it should be noted that code lengths more than 10 has more complexity and more calculation time and codes with shorter length have not good performance as the 10-length one.

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